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PARALLEL CONCATENATED TRELLIS-CODED MODULATION WITH ASYMMETRIC SIGNAL MAPPING

This application claims the priority under 35 USC 119(e)(1) of copending U.S. provisional application number 60/227,093 filed on August 22, 2000.

FIELD OF THE INVENTION

The invention relates generally to digital communications and, more particularly, to coding and modulation in digital communications.

BACKGROUND OF THE INVENTION

Each of the documents listed below is referred to herein by the corresponding number enclosed in square brackets to the left of the document. Each of these documents is also incorporated herein by reference.

[1] E. Biglieri, D. Divsalar, P. J. McLane, and M. K. Simon, *Introduction to Trellis Coded Modulation with Applications*. MacMillan, 1991.

[2] C. Berrou, A. Glavieux, and P. Thitimajshima, "Near shannon limit error-correcting coding: Turbo codes," *Proc. 1993 IEEE International Conference on Communications ICC*, pp. 1064-1070, 1993.

[3] S.L. Goff, A. Glavieux, and C. Berrou, "Turbo-codes and high spectral efficiency modulation," *Proc. 1994 IEEE International Conference on Communications ICC*, pp. 645-649, 1993.

[4] A. J. Viterbi, E. Zehavi, R. Padovani, and J. K. Wolf, "A pragmatic approach to trellis-coded modulation," *IEEE Commun. Mag.*, pp. 11-19, July 1989.

[5] P. Robertson and T. Worz, "A novel bandwidth efficient coding scheme employing turbo codes," *Proc. 1996 IEEE International Conference on Communications ICC*, pp. 962-967, 1996.

[6] P. Robertson and T. Worz, "Bandwidth-efficient turbo trellis-coded modulation using punctured component codes," *IEEE JSAC*, pp. 206-218, February 1998.

[7] S. Benedetto, D. Divsalar, G. Montorsi, and F. Pollara, "Parallel concatenated trellis coded modulation," *Proc. 1996 IEEE International Conference on Communications ICC*, pp. 974-978, 1996.

[8] S. Benedetto and G. Montorsi, "Design of parallel concatenated convolutional codes," *IEEE Trans. Commun.*, pp. 591-600, May 1996.

[9] O. Y. Takeshita, O. M. Collins, P. C. Massey, and D. J. Costello, "On the frame error rate of turbo-codes," *Proceedings of ITW 1998*, pp. 118-119, June 1998.

[10] O. Y. Takeshita, O. M. Collins, P. C. Massey, and D. J. Costello, "A note on asymmetric turbo-codes," *IEEE Communications Letters*, vol. 3, pp. 69-71, March 1999.

[11] S. Benedetto, D. Divsalar, G. Montorsi, and F. Pollara, "A soft-input soft-output APP module for interative decoding of concatenated codes," *IEEE Commun. Lett.*, pp. 22-24, January 1997.

Trellis-Coded Modulation (TCM) has been demonstrated in [1] to offer a substantial coding gain without requiring bandwidth expansion. This is achieved by appropriate joint design of coding and modulation. Turbo codes, also known as parallel concatenated convolutional codes (PCCC), were initially proposed in [2], and have been known to attain very low error rates within the signal-to-noise ratio (SNR) range close to the Shannon limit. Attempts have therefore been made to combine TCM and turbo codes to obtain a class of powerful bandwidth-efficient coded modulation schemes. One such attempt was reported in [3]. The arrangement described in [3] uses the structure of the pragmatic TCM proposed in [4]. Schemes with improved performance were later proposed in [5], [6] and [7].

The original turbo code proposed in [2] utilizes two identical recursive systematic component codes (RSCCs) in parallel concatenation with an interleaver. This turbo code attains excellent bit-error rate (BER) for low SNR values. As the SNR increases, the BER drops very quickly. However, after a certain SNR value, there is a sudden reduction in the rate at which the BER drops. This phenomenon, referred to in [8], [9] and [10] is known as the "error floor".

It is demonstrated in [9] and [10] that the error floor for the original turbo code of [2] occurs at 10^{-5} for a length-16384 interleaver. Such an error floor is not desirable for high quality data communication applications such as, for example video communications for a wireless personal area network (WPAN). Such applications can require a BER of, for example, 10^{-8}. Although the error floor for the original turbo code

can be lowered, for example, by choosing a larger interleaver size, such an adjustment disadvantageously increases system complexity and latency.

Several attempts have been made to lower the error floor without increasing the interleaver size. For example, it is shown in [8] that the error floor can be lowered by choosing the feedback polynomial of the component codes to be primitive. This essentially increases the effective Hamming distance of the turbo code (which is known from [8] to be a good measure of code performance). However, as the error floor goes down, the BER in the low SNR region (referred to herein as the waterfall region) increases (see [9] and [10]).

The authors of [9] and [10] attempted to provide for a trade-off between a low error floor and good performance in the waterfall region. In this regard, they suggested an asymmetric turbo coding structure wherein one component code has a non-primitive feedback polynomial (as in the original turbo code of [2]), and the other component code has a primitive feedback polynomial. An example of this coding structure, referred to in [9] and [10] as an asymmetric PCCC, is illustrated in FIGURE 1. In the example of FIGURE 1, the upper component code (RSCC 1) is a rate ½ RSCC with a primitive feedback polynomial, and the lower component code (RSCC 2) is a rate ½ RSCC with a non-primitive feedback polynomial. The systematic of the lower code is punctured, so the asymmetric PCCC produces coded bit outputs C_1 and C_2 from the upper branch and C_3 from the lower branch.

FIGURE 2 illustrates a conventional example of a parallel concatenated trellis-coded modulation (PCTCM) structure. In the example of FIGURE 2, the RSCC 25 and

mapping 26 for the upper and lower branches are identical. This type of structure is referred to herein as symmetric mapping PCTCM. In conventional structures such as shown in FIGURE 2, the PCTCM is typically designed using the conventional approach of searching for a component code that has good properties for a given mapping (see [6] and [7]). Typical examples of conventional mappings that are used in arrangements like FIGURE 2 include natural (set partitioning) mapping and Gray mapping. The coded bits from each component RSCC are mapped into signals S_1 and S_2 that take values within a constellation. For PCTCM, the search criterion is to maximize the effective Euclidean distance of the trellis code (see [7]). Like PCCC, PCTCM does not always provide a low enough error floor for some applications (such as the aforementioned video communication applications for WPAN). This can occur in PCTCM even when a component code that results in maximum effective Euclidean distance of the trellis code has been identified for a given mapping. This is especially true when an interleaver of moderate size is utilized.

FIGURE 3 illustrates a specific example of the PCTCM structure shown in FIGURE 2. The example of FIGURE 3 is a 2 bps/Hz PCTCM system for 16-QAM. U_1 and U_2 represent uncoded bits from a communication application. The upper (X_2 and X_1) and lower (Y_2 and Y_1) coded bits are mapped onto a 4-PAM constellation to form in-phase (I) and quadrature (Q) components, which are combined (e.g. summed) at 31 to produce the 16-QAM signal. Two different length K-bit interleavers π_1 (for LSB U_1) and π_2 (for LSB U_2) are used in FIGURE 3 to implement the interleaver section 27 of FIGURE 2. As an example, K=4096. The rate-1 RSCC G(D) with maximum effective

Euclidean distance for Gray mapping (see FIGURE 5) is used. FIGURE 4 illustrates an example of the G(D) of FIGURE 3. In particular, the G(D) shown in FIGURE 4 is the "best" 8 state RSCC G(D) for Gray mapping, and is disclosed in [7]. (The FIGURE 4 G(D) was used for both transmitter branches in all simulations described herein.)

Another possibility for the mapping in FIGURE 3 is conventional 0231 mapping, as illustrated in FIGURE 6. Again, a search could be conducted for a RSCC G(D) with good properties for the 0231 mapping.

FIGURE 3A illustrates another example of the structure of FIGURE 2. FIGURE 3A uses identical QPSK (or 8PSK) mappings at 26, and the results of the mappings are applied to a parallel-to-serial converter before transmission.

In each of the examples of FIGUREs 3 and 3A, the G(D) for one branch can differ from the G(D) for the other branch.

With respect to the example of FIGURE 3, FIGUREs 7 and 8 illustrate exemplary simulation results using Gray mapping and 0231 mapping, respectively, for $h_0 = 13$, $h_1 = 17$, $h_2 = 15$ and $K = 4096$, and assuming an additive white Gaussian noise (AWGN) channel with a power spectral density of N_0. The simulations of FIGUREs 7 and 8 plot the BER as a function of the uncoded SNR per bit, or E_b/N_0. The simulations of FIGUREs 7 and 8 use the iterative MAP decoding algorithm for PCTCM found in [11], and results for 2, 4, 6 and 8 iterations are shown. In FIGURE 7 (Gray mapping), the error floor occurs at around BER = 10^{-7}. Thus, and although the Gray mapping system provides excellent performance in the waterfall region, nevertheless it does not meet the aforementioned requirement of BER = 10^{-8}. In FIGURE 8 (0231 mapping), the error

floor is greatly reduced and is clearly below the aforementioned target of BER = 10^{-8}. However, the BER in the waterfall region is significantly higher than in FIGURE 7.

It is desirable in view of the foregoing to provide for a PCTCM system that can achieve acceptable performance in the waterfall region while also achieving an error floor that is acceptable for high quality data communication applications.

According to the invention, an error floor suitable for high quality data applications can be advantageously achieved in combination with acceptable performance in the waterfall region by providing an asymmetric PCTCM system including two component trellis code branches which utilize different coded bits-to-signal mappings.

BRIEF DESCRIPTION OF THE DRAWINGS

FIGURE 1 diagrammatically illustrates a conventional PCCC system.

FIGURE 2 diagrammatically illustrates a conventional PCTCM system.

FIGURE 3 diagrammatically illustrates a specific example of the conventional system of FIGURE 2.

FIGURE 3A illustrates another example of the system of FIGURE 2.

FIGURE 4 illustrates a portion of the conventional system of FIGURE 3 in more detail.

FIGUREs 5 and 6 illustrate conventional examples of coded bit-to-signal mapping which can be utilized in the conventional systems of FIGUREs 2 and 3.

FIGURE 7 illustrates exemplary simulation results for the system of FIGURE 3 using the mapping of FIGURE 5.

FIGURE 8 illustrates exemplary simulation results for the system of FIGURE 3 using the mapping of FIGURE 6.

FIGURE 9 diagrammatically illustrates exemplary embodiments of a PCTCM system according to the invention.

FIGUREs 9A and 9B diagrammatically illustrate specific examples of the FIGURE 9 system.

FIGURE 10 illustrates exemplary simulation results for the system of FIGURE 9.

FIGURE 11 graphically compares selected simulation results from FIGUREs 7, 8 and 10.

FIGURE 12 diagrammatically illustrates further exemplary embodiments of a PCTCM system according to the invention.

FIGURE 13 illustrates exemplary operations which can be performed by the PCTCM system of FIGURE 12.

DETAILED DESCRIPTION

FIGURE 9 diagrammatically illustrates exemplary embodiments of a PCTCM system according to the invention. In some embodiments, the coded bits of FIGURE 9 can be produced in the same conventional fashion as illustrated in FIGURE 2 or FIGURE 3. However, in the system of FIGURE 9, one branch uses a first coded bits-to-signal mapping (mapping 1) and the other branch uses a second coded bits-to-signal mapping (mapping 2) which is different than the first mapping. In some embodiments, mapping 1 is the 4-PAM Gray mapping described above which respect to FIGUREs 3 and 5, and mapping 2 is the 4-PAM 0231 mapping described above with respect to FIGUREs 3 and 6. As other examples, 6-PAM Gray mapping and 6-PAM 0231 mapping can be used. In other exemplary embodiments, first and second QPSK mappings (which differ from one another) can be used, or first and second 8PSK mappings (which differ from one another) can be used. By using different mappings for the different branches, the desired performance in the waterfall region can be advantageously balanced with the desired error floor.

The system of FIGURE 9 can be used in any desired communication transmission apparatus, for example a wireless communication apparatus or a wireline communication apparatus.. The system of FIGURE 9 receives the uncoded bits from a communication application (for example a video application for WPAN) associated with the transmission apparatus. In embodiments that use 4-PAM or 6-PAM mappings (see FIGURE 9A), the output signals S_{11} and S_{22} can be combined (as in FIGURE 3) to produce a 16-QAM signal for output to a communication channel interface which interfaces the 16-QAM

signal to a communication channel. Any desired mappings other than 4-PAM (or 6-PAM) Gray and 4-PAM (or 6-PAM) 0231 mappings can be used for mapping 1 and mapping 2 in FIGURE 9A. For example, 4-PAM (or 6-PAM) 0213 mapping can be combined with 4-PAM (or 6-PAM) Gray or 0231 mapping. In embodiments that use first and second QPSK or 8PSK mappings (see FIGURE 9B), a parallel-to-serial converter can be used (as in FIGURE 3A) to format the signals S_{11} and S_{22} for a suitable communication channel interface.

Referring again to FIGURE 9, as shown by broken line, the architecture can be extended to any desired number (N) of branches and mappers. In some embodiments, the transmission apparatus can be a wireless transmission apparatus such as provided in wireless telephones, laptop computers, personal digital assistants, etc.

In each of the examples shown in FIGUREs 9, 9A and 9B, the RSCC G(D) for one branch can be the same as or different from the RSCC G(D) for the other branch. For example, a code that is optimal for one of the mappings could be chosen for both mappings, or the optimal code for each mapping can be used with its associated mapping, or a single code for both mappings could be chosen arbitrarily, or one or two codes could be chosen empirically based on experimentation.

A suitable wireless or wireline communication receiver for receiving the signals transmitted by the transmission apparatus embodiments of FIGUREs 9, 9A and 9B can be readily implemented, for example, by modifying conventional receivers associated with the transmitters of FIGUREs 2-3A to account for the fact that the PCTCM structure of

FIGUREs 9, 9A and 9B utilizes different coded bits-to-signal mappings in the respective branches thereof.

FIGURE 10 illustrates simulation results associated with one example of the system of FIGURE 9. FIGURE 10 illustrates the relationship between BER and SNR for a 2 bps/Hz PCTCM system for 16-QAM. As discussed above with respect to FIGUREs 7 and 8, the iterative MAP decoding algorithm for PCTCM found in [11] is used, and results for 2, 4, 6 and 8 decoding iterations are illustrated. Also as in the simulations of FIGUREs 7 and 8 above, $h_0 = 13$, $h_1 = 17$, $h_2 = 15$ and the interleaver length $K = 4096$.

Comparing FIGURE 10 with FIGURE 7, it can be seen that the asymmetric mapping system of FIGURE 9 lowers the error floor from 10^{-7} to below 10^{-8} as compared to the symmetric Gray mapping system results of FIGURE 7. Comparison of FIGURE 10 with FIGURE 8 indicates that the asymmetric mapping system of FIGURE 9 realizes only a marginal performance loss of approximately 0.2 dB in the waterfall region as compared to the symmetric 0231 mapping results illustrated in FIGURE 8.

FIGURE 11 provides a graphical comparison of the 4^{th} iteration results from the symmetric Gray mapping of FIGURE 7, the symmetric 0231 mapping of FIGURE 8 and the asymmetric mapping of FIGURE 10. As shown in FIGURE 11, the asymmetric mapping of the present invention outperforms the symmetric Gray mapping with respect to error floor, while experiencing only a marginal performance loss in the waterfall region with respect to the symmetric 0231 mapping of FIGURE 8.

In the examples of FIGUREs 9, 9A and 9B, mapping 1 and mapping 2 are essentially used in the same frequency. However, as illustrated in the exemplary

embodiments of FIGURE 12, mapping 1 and mapping 2 need not be used in the same frequency. Moreover, as shown in FIGURE 12, both mapping 1 and mapping 2 can be used to produce the signal S_{11}, and both mapping 1 and mapping 2 can be used to produce the signal S_{22}.

In the example of FIGURE 12, the coded bits at 21 and the interleaved version of the coded bits at 22 are input to respective selectors 121 and 122. These selectors are responsive to control signals received from a controller 123 for routing their associated coded bits to either a mapper that performs mapping 1 or a mapper that performs mapping 2. Thus, signal S_{11} can be produced using both mapping 1 and mapping 2, and signal S_{22} can similarly be produced using both mapping 1 and mapping 2. The controller 123 receives relative frequency information and controls the selectors 121 and 122 appropriately in response to this information, so that the signals S_{11} and S_{22} reflect the desired relative frequency combination of mapping 1 and mapping 2. The relative frequency information can, in some embodiments, include a relative frequency parameter ρ. This relative frequency parameter can be used to control a trade-off between waterfall performance and error floor performance. Different values of ρ that respectively correspond to different combinations of waterfall/error floor performance can be determined, for example, from simulations and/or experimental observations, and the values of ρ can then be stored, for example, in a look-up table, indexed against the corresponding combinations of waterfall/error floor performance.

FIGURE 13 illustrates exemplary operations which can be performed by the system of FIGURE 12 to produce the signals S_{11} and S_{22}. At 131, the value of ρ is

determined. If $\rho = \infty$, then at 132 only mapping 1 is used for both S_{11} and S_{22} (conventional symmetric mapping for mapping 1), until a new value of ρ is provided at 134. If $\rho = 0$, then at 133 only mapping 2 is used for both S_{11} and S_{22} (conventional symmetric mapping for mapping 2), until a new value of ρ is provided at 134. If ρ is neither 0 nor ∞, then at 136, mapping 1 is used ρ times as frequently as is mapping 2, until a new value of ρ is provided at 134. For example, if $\rho = 3$, then mapping 1 can be used exclusively to produce S_{11} in FIGURE 12, while controller 123 controls selector 122 such that mapping 1 and mapping 2 can be used alternately to produce alternate symbols of S_{22}. If $\rho = 1/3$, then, for example, mapping 2 can be used exclusively for S_{22} while mapping 1 and mapping 2 are used alternately to produce alternate symbols of S_{11}.

Note, for example, that when each mapping is to be used in the same frequency ($\rho = 1$), this can be realized, for example, by using only mapping 1 to produce S_{11} and using only mapping 2 to produce S_{22}. However, in some embodiments, the controller 123 can control the selectors such that each of the signals S_{11} and S_{22} is produced using both mapping 1 and mapping 2. In such embodiments, each mapping can be used in the same frequency ($\rho = 1$), for example, by using mapping 1 and mapping 2 alternately to produce alternate symbols in S_{11}, and correspondingly using mapping 2 and mapping 1 alternately to produce alternate symbols in S_{22}. That is, the symbol mapping sequence for S_{11} would be mapping 1, mapping 2, mapping 1, mapping 2, etc., while the timewise corresponding sequence for S_{22} would be mapping 2, mapping 1, mapping 2, mapping 1, etc. In general, a "both switch" signal can be activated at an input of the controller 123 to indicate that both mapping 1 and mapping 2 are to be used to produce each of the signals S_{11} and S_{22}.

The controller 123 then controls the selectors 121 and 122 such that both mappings are used to produce both signals S_{11} and S_{22}, while still complying with the relative frequency parameter ρ. Any desired symbol mapping sequences can be used for S_{11} and S_{22},, provided that they comply with the selected value of ρ.

It will be apparent to workers in the art that the invention described above can be readily implemented by suitable modifications in software, hardware or a combination of software and hardware in conventional communication transmission and receiver stations.

Although exemplary embodiments of the invention are described above in detail, this does not limit the scope of the invention, which can be practiced in a variety of embodiments.